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Isospin breaking exposed in $f_0(980) - a_0(980)$ mixing

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Abstract

We suggest that mixing between the $f_0(980)$ and $a_0(980)$, due to their dynamical interaction with the nearby $K\bar{K}$ thresholds, can give rise to a significantly enhanced production rate of $a_0(980)$ relative to $a_2(1320)$ in $pp \to p_s(\eta\pi^o)p_f$ as $x_F \to 0$. The peaking of the cross section as $\phi \to 0$ should also occur. We show that such effects are seen in data and deduce that the $f_0(980) - a_0(980)$ mixing intensity is 8 ± 3 %.

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The enigma of the scalar mesons may be boiled down to an essential question: what are the $f_0(980)$ and $a_0(980)$? Do they have a common origin and, if so, what is it? Understanding the $f_0(980)$ in particular is a central problem for identifying the dynamics associated with the long sought scalar glueball.

There have even been suggestions that the $f_0(980)$ itself may be the eponymous glueball, perhaps mixed with $q\bar{q}$; in such a case the mass degeneracy with the $a_0(980)$ would be somewhat accidental and the two mesons not clearly related. An interpretation of the $f_0(980)$ as a $q\bar{q}$ state is still consistent with the present data (see for example ref. [1]). By contrast, there is a large body of work drawing on the observation that the $f_0(980)$ and $a_0(980)$ are very close to the $K\bar{K}$ threshold, and that the $K\bar{K}$ channel drives the dynamics [2]. As an extreme, there is the possibility that these mesons are truly bound states of $K\bar{K}$ [3].

Traditionally in strong interactions isospin is believed to be a nearly exact symmetry, broken only by the slightly different masses of the u and d quarks and/or electroweak effects. The small difference in mass between $K^{\pm}$ and K^0 is a particular example. However, the mass gaps between the $f_0(980)/a_0(980)$ and the K^+K^- and K^0K^0 thresholds are substantially different with the result that the dynamics of bound $K\bar{K}$ states can be described better in a basis specified by mass eigenstates. Such dynamics would give rise to a violation of isospin and lead to mixing of states with different G-parities.

The possibility of such an effect was suggested long ago in ref. [4]. In ref. [5] a study was performed of the production of the $a_0(980)$ in the reaction $\pi^+\pi^- \to \eta\pi$ which due to G parity is forbidden and can only occur through $f_0(980) - a_0(980)$ mixing. This showed that (6–33)% of the $a_0(980)$ cross section in $\pi^- p$ reactions could be due to $f_0(980) - a_0(980)$ mixing. Further discussions along this line have been made by ref. [6] who have specifically drawn attention to the relation between the existence of $K\bar{K}$ molecular bound states and large violations of isospin. Very recently, attention has been drawn to such mixings having observable effects in threshold photoproduction, such as at CEBAF [7]. These papers have all concentrated on the production of the $f_0(980)/a_0(980)$ by flavoured mesons or photons; in this paper we propose that their production by gluonic systems, such as the $I\!P$(Pomeron)-induced production in the central region at high energy: $pp \to pp + f_0(980)/a_0(980)$, may provide rather clean tests of the mixing. Furthermore, we shall suggest that new data from the WA102 collaboration at CERN [8] are already consistent with a significant mixing. We shall consider alternative interpretations and suggest ways of eliminating these in future experiments.

These data potentially may help to elucidate the nature of the $f_0(980)/a_0(980)$ states. Our hypothesis is based on recent breakthroughs in understanding the dynamics and topology (momentum and spatial distributions) of meson production in the central region of rapidity, $pp \to pMp$ [9, 10]. In particular, we shall focus on the description of the observed ϕ dependences [10], where ϕ is the angle between the p_T vectors of the two outgoing protons. In such processes at high energy, where $I\!P I\!P$ fusion dominates the meson production, $C = +, I = 0$ resonances such as the $f_0(980)$ are very strongly produced [11] whereas in general isospin 1 states are suppressed [12]. Even at the energies of the WA102 data, there is considerable evidence that $I\!P I\!P$ fusion is an important part of the production dynamics [12]. It is tantalising therefore that recent data from the WA102 collaboration on the centrally produced $\eta\pi$ final state [8] show interesting effects in that they are in accord with substantial $f_0(980) - a_0(980)$ mixing.

In particular it is instructive to compare the systematics of the well understood $f_2(1270)/a_2(1320)$ $(^3P_2 q\bar{q})$ states with the $f_0(980)/a_0(980)$ states. In the reaction $pp \to p(\eta\pi^o)p$ the centrally produced $a_0(980)$ and $a_2(1320)$ are suppressed relative to their $I = 0$ partners, as expected for $I = 1$ states. Nonetheless, there appears to be an extra affinity for $a_0(980)$ production here, since

$$\frac{\sigma(pp \to pp[a_0^0(980) \to \eta\pi])}{\sigma(pp \to pp[a_2^0(1320) \to \eta\pi])} \approx 2.0 \pm 0.4 \tag{1}$$

By contrast, when the charged members of these isovectors are produced, as in $pp \to p(\eta\pi^-)\Delta^{++}$, $a_0^-(980)$ and $a_2^-(1320)$ production rates are found to be similar. Fits to the $\eta\pi^-$ mass spectrum in central production give

$$\frac{\sigma(pp \to p\Delta^{++}[a_0^-(980) \to \eta\pi^-])}{\sigma(pp \to p\Delta^{++}[a_2^-(1320) \to \eta\pi^-])} \approx 0.8 \pm 0.2 \tag{2}$$

The significance of these ratios becomes more apparent when compared with the case of the charge exchange reaction, where (as in eq. (2)) $I = 1$ exchanges are necessarily present. In this case the $a_2(1320)$ meson dominates the mass spectrum, and the ratio

$$\frac{\sigma(\pi^- p \to [a_0(980) \to \eta\pi]n)}{\sigma(\pi^- p \to [a_2(1320) \to \eta\pi]n)} \approx 0.15 \tag{3}$$

at 38 GeV/c beam momentum.

First we shall explain this hierarchy and motivate the enhancement in (1) as indicative of direct $f_0(980)$ production with $f_0(980) - a_0(980)$ mixing. Then we show how the characteristic momentum and ϕ dependences of $f_0(980)$ production will, through mixing, spill over to $a_0(980)$ production. Finally we shall see that such signatures are indeed present in the $a_0(980)$ production data and consistent with a substantial $f_0(980) - a_0(980)$ mixing.

In $\pi^- p \to a_{0,2} n$ (3), it is easy to make the $a_2(1320)$ via ρ exchange. However in order to produce the $a_0(980)$, ρ_2 and/or b_1 exchange is needed which is relatively suppressed [5]. In $pp \to p(\eta\pi^-)\Delta^{++}$ (2) the a_2 production is again consistent with $\pi\rho$ fusion [8]. Fig. 1b) shows the observed ϕ distribution for the $a_2^-(1320)$ [8]. As can be seen the distribution is isotropic in ϕ, as expected for π exchange [9, 13], and the t slopes [8] are consistent with π and ρ being produced at either vertex, (it is known that the ρ can be produced at the $p\Delta^{++}$ vertex from the WA102 data on $pp \to p\Delta^{++}\rho^-$ [14]). However, some other mechanism is needed to explain the relatively enhanced $a_0(980)$ signal. The ϕ distribution for the $a_0^-(980)$ is shown in fig. 1a) and as can be seen it is also isotropic.

There are four particular exchanges that can enhance the $a_0(980)$ signal in $pp \to p(\eta\pi^-)\Delta^{++}$ (2)relative to its suppressed rate in charge exchange (3). First, I=0 exchange (η) can occur at the proton vertex and cause $\pi\eta \to a_0(980)/a_2(1320)$. Though η exchange will be isotropic in ϕ, in accord with data, it is generally agreed to be small and hence unlikely on its own to drive the enhanced $a_0(980)$ signal.

The second possibility is production by πb_1 fusion. Although the ppb_1 vertex is small, for $p\Delta b_1$ the quantum numbers match in $S-$wave and so πb_1 fusion could be significant in

$pp \to p\Delta a_{0,2}$. Because of the π exchange, the ϕ distribution will be isotropic [9, 13], as in the data. However, empirically $\sigma(pp \to ppa_2(1320)) \sim \sigma(pp \to p\Delta a_2(1320))$ which suggests that b_1 exchange is not the major mode and further points to $\pi\rho \to a_2(1320)$ as the dominant dynamics. If $a_0(980) = {}^3P_0(q\bar{q})$ then in the quark model the ratio of amplitudes $\pi b_1 \to a_0(980)/a_2(1320) \sim 1$ and we would still be left with the mystery of its production. Even if $a_0(980) \neq {}^3P_0(q\bar{q})$, the πb_1 production would be expected to be minimal in pp and so the enigma of $a_0(980)$ production there would remain.

The third possibility is that ρ from the $p\Delta$ vertex fuses with ω from the pp vertex. This can feed both $a_0(980)$ and $a_2(1320)$. Empirically the $a_2(1320)$ is produced polarised with $\lambda = 1$ [8]; however, $VV \to 2^{++}(\lambda = 1)$ would contain a characteristic $\sin^2(\phi/2)$ component [9] in marked contrast to the observed isotropy. This suggests that $\rho\omega \to a_2(1320)$ is not a major mechanism and to the extent that $a_{0,2}$ are related as ${}^3P_{0,2}$ $q\bar{q}$ states, would also argue against a strong $a_0(980)$ signal. Furthermore, the empirical absence of $a_2(1320)({}^3P_2 q\bar{q})$ with $(\lambda = 0)$ would in turn also imply a suppressed production of $a_0(980)({}^3P_0 q\bar{q})$. However, it is possible that the $K\bar{K}$ threshold disturbs the $a_0(980)$ such that $\rho\omega \to a_0(980)$ is controlled by this and not by the $q\bar{q}$ content; in this case the production strength and properties could be independent of the $a_2(1320)$. In general the ϕ dependence for a 0^{++} state produced by vector-vector fusion (where L is the the longitudinal component of the vector and T is the transverse component) has the following structure [10]:

$$\frac{d\sigma}{dt_1 dt_2 d\phi} \sim [1 + \frac{\sqrt{t_1 t_2}}{\mu^2} \frac{a_T}{a_L} e^{(b_L - b_T)(t_1+t_2)/2} \cos(\phi)]^2 e^{-b_L(t_1+t_2)} \tag{4}$$

The ratio a_T/a_L, which determines the relative importance of the 0^+ production by T or L components,can be positive or negative, or in general even complex; its value is determined, inter alia, by the internal dynamics of the produced meson. To the extent that the ϕ distributions empirically are consistent with being isotropic, it would appear that longitudinal-scalar amplitudes dominate the production for the $a_0(980)$; this might be natural were it a $K\bar{K}$ molecule where K exchange dominated the production vertex.

The fourth possibility is that $I\!\!P$ exchange plays a role at the pp vertex. In principle there could be significant $a_{0,2}$ $I\!\!P \to a_{0,2}$. If these were dominant, one would expect similar production rates of $a_0(980)$ in both $ppa_0(980)$ and $p\Delta a_0(980)$ processes and also a rapid fall off in the $a_0(980)/a_2(1320)$ production ratio with increasing energy. As the data are only at a single value of s one cannot immediately eliminate this. However there are two features that argue against this. First, $a_0(980)$ $I\!\!P \to a_0(980)$ will give an isotropic ϕ distribution; while this is seen in the $p\Delta a_0(980)$ production (fig. 1a), the reaction $ppa_0(980)$ is ϕ dependent (fig. 2a). Second; the x_F distributions of the $a_0^-(980)$ and $a_2^-(1320)$ formed in $p\Delta a_{0,2}$ are shown in fig 1c) and d) respectively. As can be seen the distributions are flat for $x_F \leq 0.1$ (do not peak as $x_F \to 0$) which may indicate that there is a significant presence of non-central production. Fig 2c) and d) show the x_F distributions for the $a_0^0(980)$ and $a_2^0(1320)$ formed in $ppa_{0,2}$. The distribution for the $a_2^0(1320)$ is similar to that observed for the $a_2^-(1320)$ whereas that for the $a_0^0(980)$ is significantly different and peaks at $x_F = 0$. Indeed this is the only state with $I = 1$ that is observed to have a x_F distribution peaked at zero [15], and moreover the distribution for the $a_0^0(980)$ looks similar to the central production of states that are accessible to $I\!\!P I\!\!P$ fusion, in particular $I\!\!P I\!\!P \to f_0(980)$, see fig 3c) and d). If we restrict ourselves to the central production region $x_F \leq 0.1$, then the relative ratio of a_0/a_2 production rates in eq. (1) is even more enhanced and becomes 3.4 ± 0.4 .

In summary, we are unable to find an explanation of the production of a_0 in $pp \to p\Delta a_0$ if $a_0 = {}^3P_0 q\bar{q}$. We will now show evidence that there is significant mixing between $a_0^0(980)$ and $f_0(980)$ in $pp \to ppa_0/f_0$, which reveals a marked affinity of these states for $K\bar{K}$.

In the process $pp \to p(\eta\pi^0)p$ (1), there is a prominent new feature allowed, namely $I\!\!P I\!\!P$ fusion due to $I\!\!P$ emission at each proton vertex. As this will feed only $I = 0$ channels, such as the $f_0(980)$ and $f_2(1270)$, one would not expect this to affect $a_{0,2}$ production unless isospin is broken. As we noted earlier, the $a_0(980)/a_2(1320)$ ratio in the WA102 data is significantly larger in reaction (1) than in reaction (2), especially so when $x_F \leq 0.1$. Furthermore, the x_F distribution of the $a_0(980)$ production is, within the errors, identical to that of the $f_0(980)$ (see fig. 3d)). In reaction (2) the ϕ dependencies for both the $a_0(980)$ and $a_2(1320)$ are flat (fig. 1a) and b) respectively). In reaction (1) although the ϕ dependence of the $a_2(1320)$ remains flat (fig. 2b)) that of the $a_0(980)$ is peaked as $\phi \to 0$ (fig. 2a)). In fact the ϕ distribution for the $a_0(980)$ looks very similar to that observed for the $f_0(980)$ (fig. 3a) and c)). Qualitatively this is what would be expected if part of the centrally produced $a_0^0(980)$ is due to $I\!\!P I\!\!P \to f_0(980)$ followed by mixing between the $f_0(980)$ and the $a_0(980)$.

In order to estimate the amount of the $a_0^0(980)$ that has been produced by mixing we have performed a fit to the ϕ distribution of the $a_0^0(980)$ assuming it to be the sum of two incoherent components: (i) a flat distribution similar to the $a_0^-(980)$ and (ii) a distribution of the form $(4 + \cos(\phi))^2$ which describes the ϕ distribution of the $f_0(980)$ as shown in fig 3a). We have determined from the fit to fig. 2a) that 80 ± 25 % of the $a_0^0(980)$ comes from the $f_0(980)$. Combining this result with the relative total cross sections for the production the $f_0(980)$ and $a_0^0(980)$ [15] we find the $f_0(980) - a_0(980)$ mixing intensity to be 8 ± 3 %.

Technically our analysis only sets an upper limit on the isospin breaking until such time as the energy dependence is determined and the $I\!\!P I\!\!P$ production thereby confirmed. Subject to this caveat our analysis adds weight to the hypothesis that the $f_0(980)$ and $a_0(980)$ are siblings that strongly mix, and that the $a_0(980)$ is not simply a ${}^3P_0 q\bar{q}$ partner of the $a_2(1320)$. A natural explanation of these results would be that the $K\bar{K}$ threshold plays an essential role in the existence and properties of these states. The question of whether they are $K\bar{K}$ bound states or whether it is merely the $K\bar{K}$ threshold which is driving these effects is still to be resolved.

Other lines of study are now warranted. Experimentally to confirm these ideas requires measuring the production of the $\eta\pi$ channel at a much higher energy, for example, at LHC, Fermilab or RHIC where Reggeon exchanges such as $\rho\omega$ would be effectively zero and hence any $a_0(980)$ production must come from isospin breaking effects. In addition, "pure" flavour channels should now be explored. Examples are D_s decays [16] where the weak decay leads to a pure I=1 light hadron final state. Thus $\pi f_0(980)$ will be (and is [17]) prominent, while our analysis would suggest that πa_0 should also be present at 8 ± 3 % intensity. We recommend that these be studied with high statistics data sets now emerging from E791, FOCUS and BaBar. In addition, we encourage studies of J/ψ decays at Beijing, in particular to the "forbidden" final states ωa_0 and ϕa_0 where we predict branching ratios of $O(10^{-5})$. On the theory side, detailed predictions are needed in specific models in order to resolve precisely how the $K\bar{K}$ threshold relates to the $f_0(980)/a_0(980)$ states.

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Figures

Figure 1: For the reaction $pp \rightarrow \Delta^{++} p \eta \pi^-$: The ϕ distributions for a) the $a_0^-(980)$ and b) the $a_2^-(1320)$. The x_F distributions for c) the $a_0^-(980)$ and d) the $a_2^-(1320)$.

Figure 2: For the reaction $pp \rightarrow pp\eta\pi^0$: The ϕ distributions for a) the $a_0^0(980)$ and b) the $a_2^0(1320)$. The x_F distributions for c) the $a_0^0(980)$ and d) the $a_2^0(1320)$.

Figure 3: The ϕ distributions a) for the reaction $pp \rightarrow ppf_0(980)$ and b) for the $f_0(980)$ compared to the $a_0^0(980)$. The x_F distributions c) for the reaction $pp \rightarrow ppf_0(980)$ and d) for the $f_0(980)$ compared to the $a_0^0(980)$.

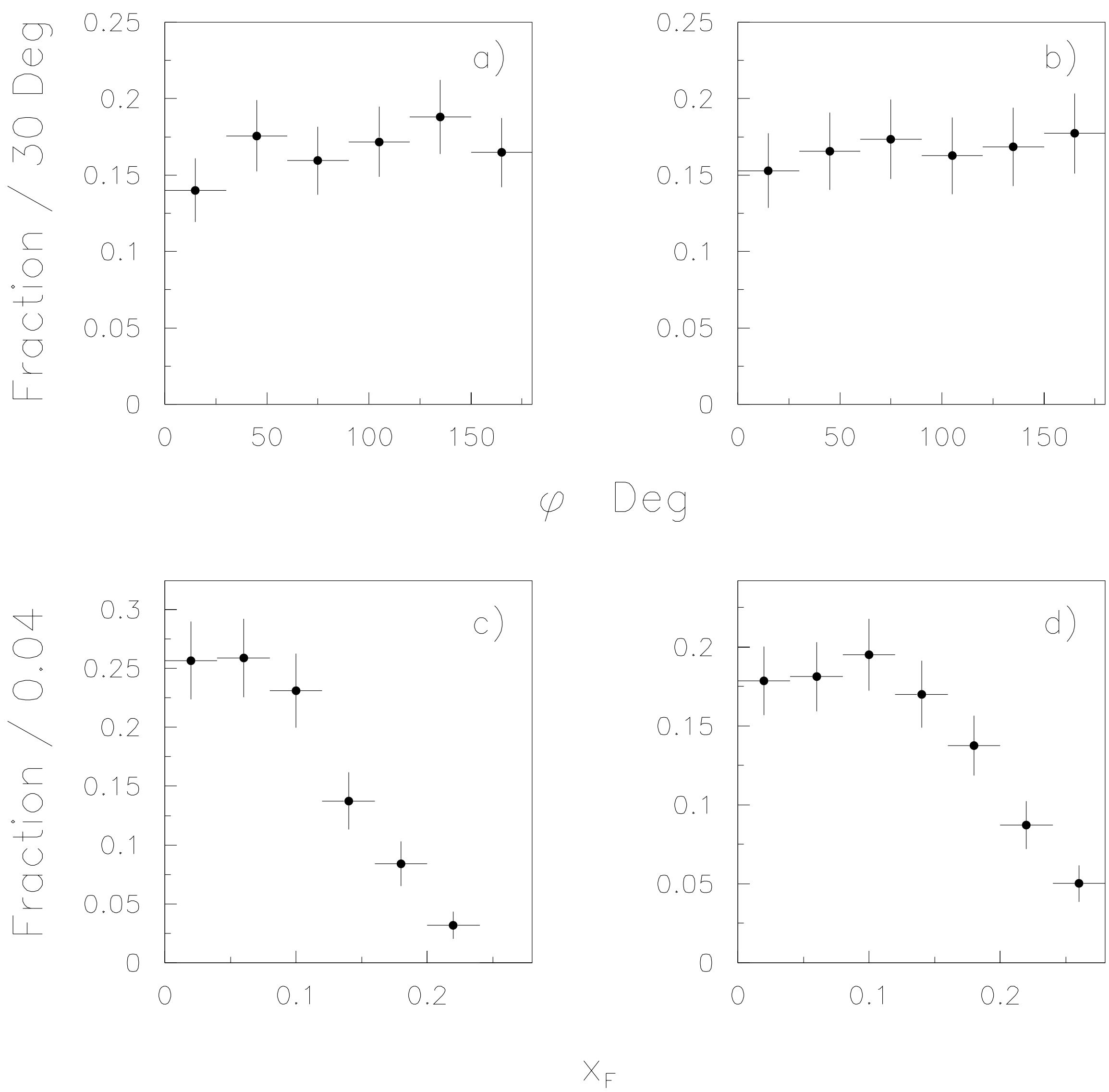

Figure 1

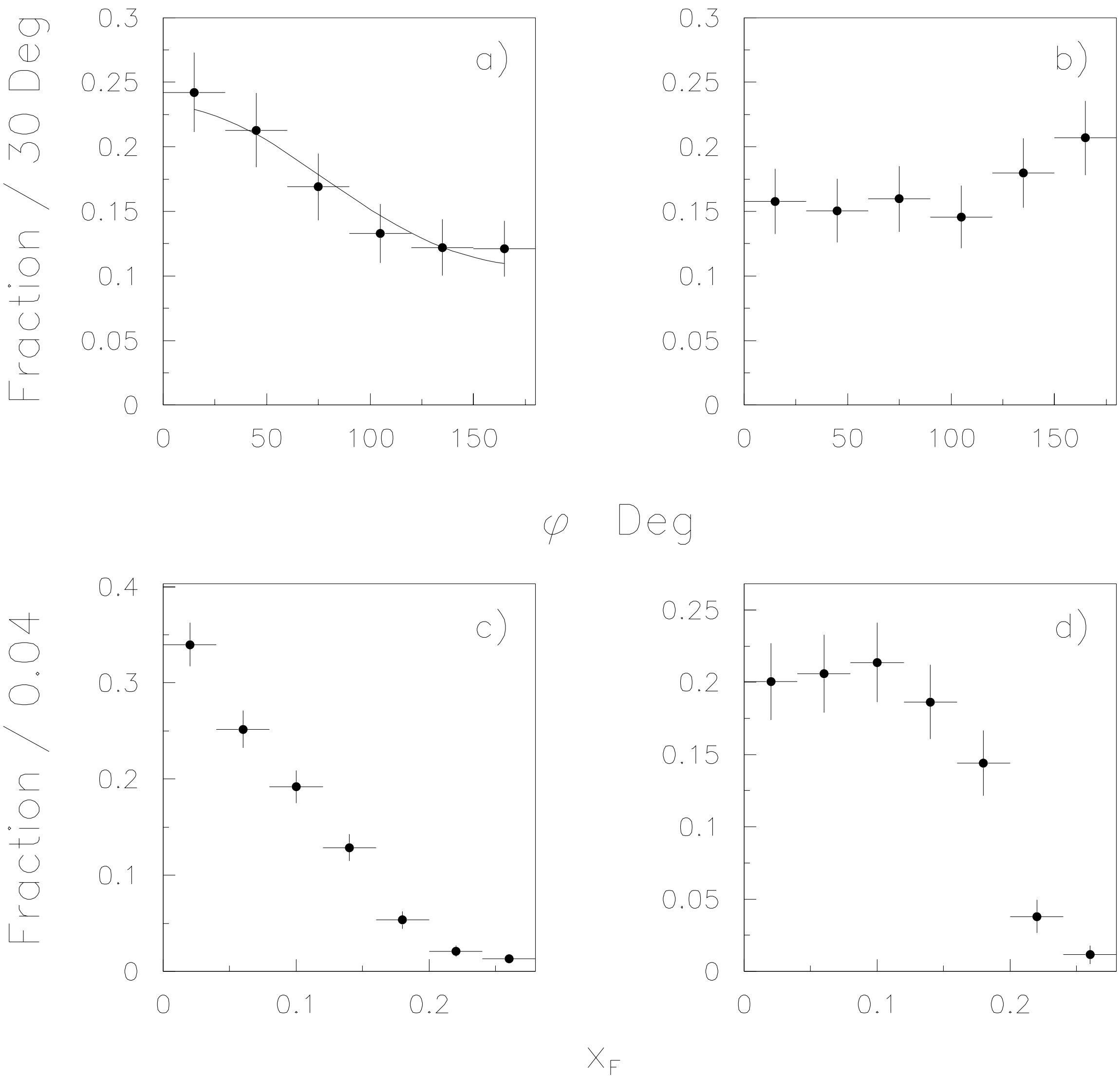

Figure 2

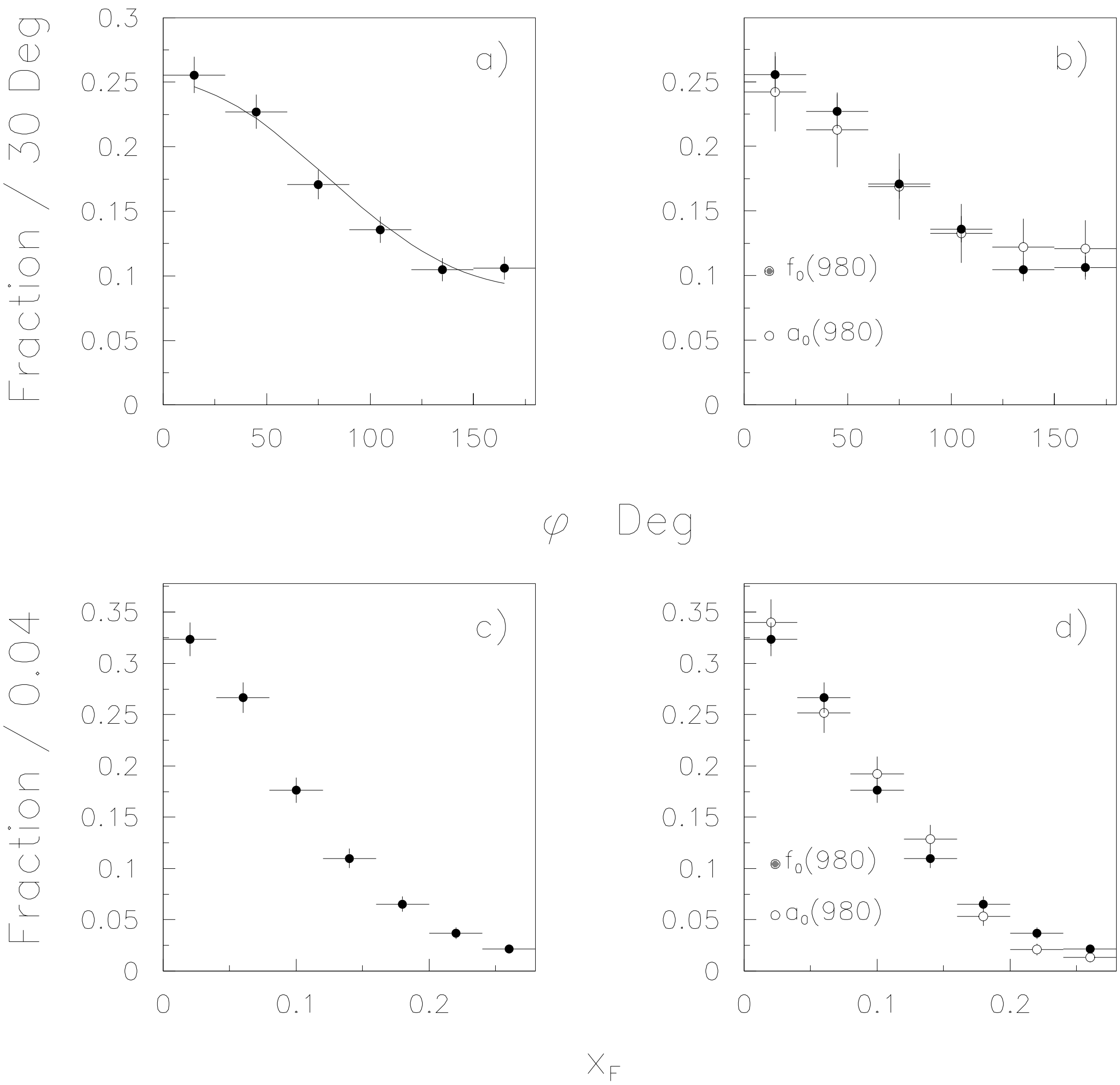
Fraction / 30 Deg
a)
b)
$f_0(980)$
$a_0(980)$
φ Deg
Fraction / 0.04
c)
d)
$f_0(980)$
$a_0(980)$
x_F

Figure 3